

CHANDRA OBSERVATIONS OF THE GRAVITATIONAL POTENTIAL STRUCTURE IN ABELL 1060

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ABSTRACT

We present results from a Chandra observation of Abell 1060, the nearby isothermal cluster of galaxies. The ACIS-I image shows that the central cusp-like structure, previously seen from PSPC, is caused mainly by an emission from the central elliptical galaxy NGC 3311. We confirmed that the central region is remarkably isothermal with a temperature of 3.2 keV, based on the spectral fits for fine pixels. An extended region in the northeast of NGC 3311 indicates high iron abundance. The surface brightness profile excluding the central galaxy, NGC 3311, can be fitted only by a double β model, with core radii about 40 and 140 kpc, out to a radius of about 200 kpc. This suggests that the gravitational potential in Abell 1060 consists of 2 components.

Key words: galaxies: clusters: individual (Abell 1060) — intergalactic medium — X-rays: galaxies

1. INTRODUCTION

The gravitational potential structures of clusters have been probed mainly by X-ray observations of the intracluster medium (ICM). ICM distributions are empirically represented well by an isothermal β model, which approximates the gas density profile given by the King-type potential with a flat density core under the assumption of hydrostatic equilibrium. On the other hand, recent numerical simulations (e.g. Navarro, Frenk, and White 1996) involving a large number of test particles indicate that the potential profile takes a universal form with a cusp structure in the central ~ 50 kpc region. For an observational determination of the gravitational potential structure, an X-ray observation with high angular resolution is the most powerful way because it enables us to map out the gas density and temperature right into the center of the cluster.

Abell 1060 (hereafter A1060) is an X-ray bright cluster of galaxies at a redshift of $z = 0.0114$. There are two giant elliptical galaxies in the center, NGC 3311 as a central cD galaxy and NGC 3309. Previous X-ray observations with ROSAT and ASCA have shown that A1060 has circularly symmetric surface brightness, an average temperature of 3.3 keV, and a constant abundance of 0.3 solar (Tamura et al. 1996, Tamura et al. 2000, Furusho et al. 2001). Any

significant feature of a cool component or cooling flow is almost absent in the spectrum of the central region. The cluster optical morphology showed that A1060 is remarkably isolated in redshift space (Richter et al. 1982). These unique properties allow us to look into the gravitational potential structure which is almost free from external effects such as subcluster mergers.

In this paper, we use $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$, which indicates $1'' = 0.217 \text{ kpc}$ and $1' = 13 \text{ kpc}$ at the cluster. The solar number abundance of Fe relative to H is taken as 4.68×10^{-5} (Anders and Grevesse 1989).

2. OBSERVATION AND ANALYSIS

The Chandra observation was performed on 2001 June 4 with ACIS-I, consisting of CCD chips I0123, and S2, for an exposure time of 32 ks. The data were obtained with the Very Faint mode. The cluster center was focused at the center of I3 chip. Except for 1–2 ks at the end of the observation, the count rate in the energy band 0.3–10 keV stayed almost constant at 4.1 counts s^{-1} for the I3 chip, and 2.9 counts s^{-1} for the I012 chips, respectively. Since the contribution from the particle background was relatively high in I012 chips, which do not cover the cluster center, we excluded all the time intervals when the count rates of these chips exceeded 3.2 counts s^{-1} . This screening resulted in a useful exposure time of 29.8 ks. The background image and spectrum were subtracted based on the blank sky data prepared by M. Markevitch (<http://asc.harvard.edu/cal/>). The average background count rate was 0.27 count $\text{s}^{-1} \text{ chip}^{-1}$ in the 0.3–10 keV band, which was less than the cluster flux by a factor of about 10 and 4 for the I3 and I012 chips, respectively.

3. RESULTS

3.1. THE CENTRAL REGION

The X-ray image of the central 6.6×6.6 region of the cluster taken with the I3 chip is shown in Figure 1. Contours are smoothed by a Gaussian function with $\sigma = 4''$, and corrections for background and exposure time are performed. The central elliptical galaxies, NGC 3311 and NGC 3309, are clearly resolved, and a diffuse excess emission in the northeast of NGC 3311 is also revealed. The

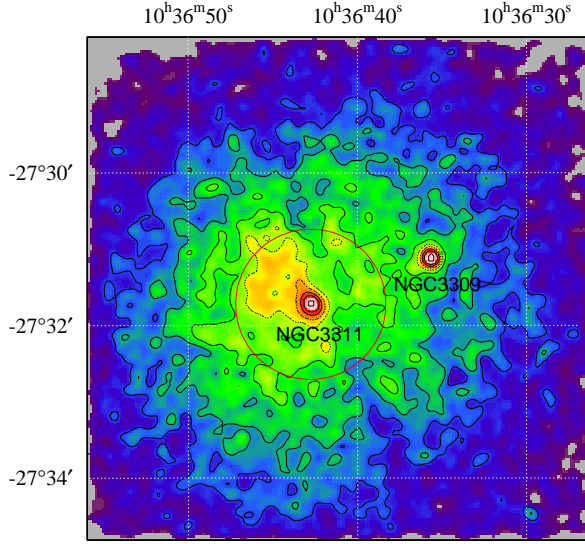


Figure 1. The central ACIS-I3 image of A1060 in 0.5–10 keV band. The red circle shows roughly the optical size with a radius of $1' = 13$ kpc.

X-ray properties of the two elliptical galaxies are described in Yamasaki et al. (2002). Here, we report on the northeast emission of NGC 3311.

Figure 2 shows the spectrum for the northeast annulus with a radius range of $20'' - 50''$, compared with that in the opposite southwest region. Both spectra indicate a similar temperature of about 3 keV, which is consistent with the ICM level. However, their Fe-line features are markedly different. The best-fit abundance is as high as 1.0 solar for the northeast region, much higher than the 0.3 solar observed both in the southwest region and in the general ICM of A1060. The excess X-ray luminosity in this region is estimated to be several $\times 10^{40}$ erg s^{-1} , which is comparable to the emission of NGC 3311 itself. We note that the region with the anomalous abundance is located within the isophotal radius of NGC 3311 (21 kpc, Västerberg et al. 1991).

3.2. TEMPERATURE MAP

The temperature map of A1060 derived from hardness ratio analysis on the ASCA GIS data showed that the ICM is almost isothermal with an average temperature of 3.3 keV in a scale of $5'$ over the whole cluster (Furusho et al. 2001). The angular resolution of Chandra allows us to perform spectral fits in much smaller scales, since the data are not affected by stray light and energy-dependent PSF effects. To produce the temperature map with sufficient statistics, we divided the image into 9 annulus regions, which are further divided into 2–4 azimuthal sections. Point source

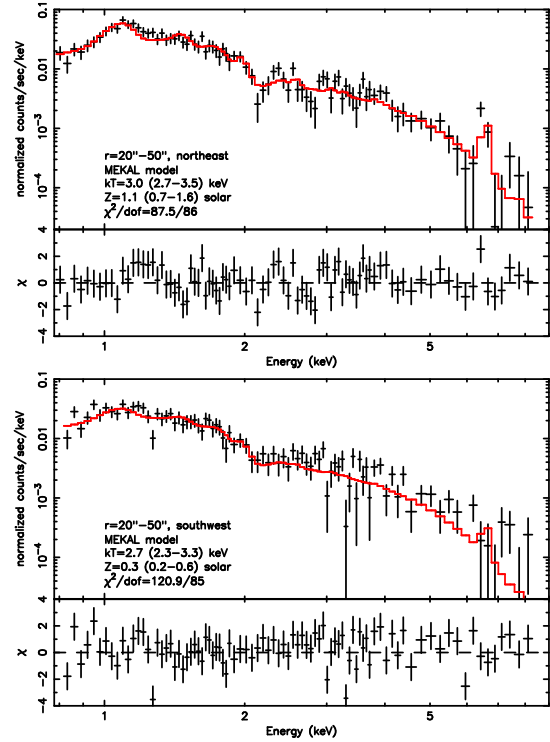


Figure 2. Pulse-height spectra and best-fit absorbed MEKAL model for the northeast (top) and southwest (bottom) annular regions of the NGC 3311 with a radius of $20'' - 50''$.

candidates and NGC 3309 were masked out with a circle of $20''$ radius.

The spectra can be represented by an absorbed MEKAL model, however, all the data showed absorption features that were considerably in excess of the Galactic value of $N_H = 6 \times 10^{20}$ cm^{-2} . Since no significant absorption was seen in the PSPC data, this is likely to be caused by an incorrect response function in the low energy band. To derive the temperature, we tried two methods. One was to fit the spectra in the energy band 0.8–8 keV by adjusting N_H as a free parameter, and the other was the fit in 2–8 keV with fixed N_H at the Galactic value. The temperature difference between the two fits is very small and 0.5 keV at most. The typical statistical errors are 0.3 keV at the 90% confidence.

The resultant temperature map based on the free N_H fit is shown in Figure 3. It is shown that the temperature distribution in the ICM is very uniform with a temperature around 3.2 keV. The most inner regions at the south of NGC 3311 give slightly lower temperatures of ~ 2.5 keV. This small temperature drop at the center is considered to be caused by a contamination of NGC 3311 component, not a cooling flow.

Figure 3. Color-coded temperature map of the ACIS-I. The contours indicate the X-ray image smoothed by a Gaussian function with $\sigma = 8''$.

3.3. SURFACE BRIGHTNESS AND MASS PROFILES

Figure 4 shows the surface brightness profile in the 0.5–10 keV energy band after subtraction of the background, point sources, and the diffuse emission in the northeast of NGC 3311. The data are fitted with single β and double β models for the region of $20'' < r < 15'$. The single β fit gives $r_c = 46.0 \pm 1.2$ kpc and $\beta = 0.51 \pm 0.1$, which are both slightly different from the PSPC results of $r_c = 50.7 \pm 1.3$ kpc and $\beta = 0.54 \pm 0.1$ (Tamura et al. 2000). This may be due to the changes of covered energy band and the observed area, for which the PSPC parameters were 0.5–2 keV and $r < 60'$. The profile is, however, not simply described by the single β model indicating $\chi^2/dof = 823.3/465$. The NFW model gives $\chi^2/dof = 694.4/464$, which is not a good fit either. If we fit the profile by changing the outer cut-off radius in $r = 3' - 15'$, the best-fit core radius and β increase with the cut-off radius. Based on this feature, we tried a double β model, which could fit the data well showing $\chi^2/dof = 532.8/462$. The best-fit core radii were obtained to be 41.5 and 142.7 kpc with $\beta = 0.82$ and 0.94, respectively. These values are close to the 2 peaks (40 and 173 kpc) in the distribution of core radius for 79 distant ($z > 0.1$) clusters, recently studied by Ota (2001).

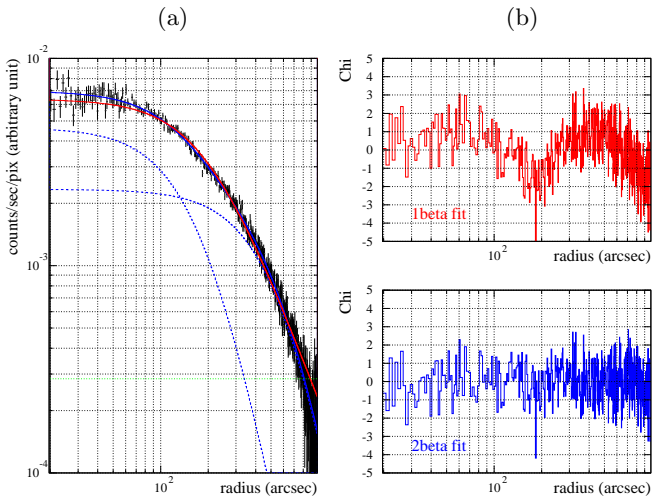


Figure 4. (a) X-ray surface brightness profile and the best-fit single (red) and double (blue) models with the subtracted background level (green dotted line). (b) The residual from the best-fit single (top) and double (bottom) β models.

Because of the symmetric morphology and the isothermality seen in the temperature map, it is a reasonable assumption that this cluster is in a hydrostatic equilibrium. Under this assumption, we can estimate the total gravitating mass profile for the single and double β models, as shown in Figure 5. The mass profile assuming the modified Hubble law is also shown for comparison. There is some difference between the mass distributions for the single and double β models, and the modified Hubble law which is the approximation of the King potential gives a similar profile with the single β case.

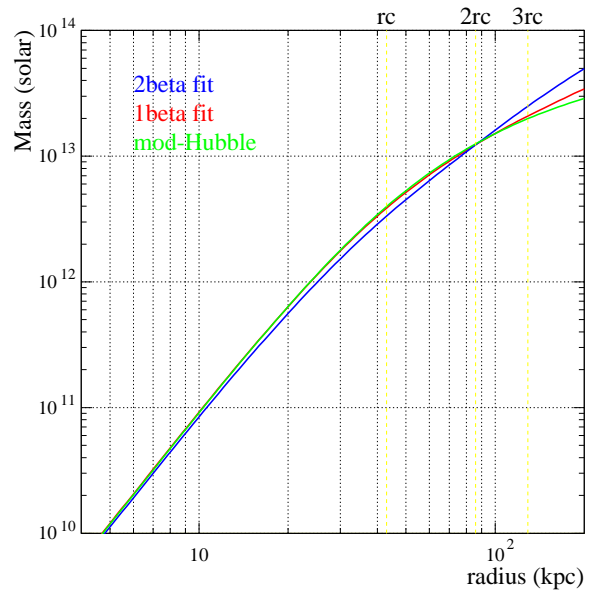


Figure 5. Total mass profiles from the single (red) and double (blue) β models, and modified Hubble model (green). The r_c at the top indicates 44 kpc that is the best-fit core radius fitted with a single β model.

4. DISCUSSION

The excess X-ray emission extending to the northeast of the central galaxy NGC 3311 indicated an unusually high metal abundance with a temperature of about 3 keV. One possibility is that the metal rich gas was ejected from NGC 3311 by a galactic wind, which may be heated by a collision with the surrounding ICM. The excess region is, however, located inside the galaxy in the optical band, and the size and mass of NGC 3311 are smaller than those of typical cD galaxies. Also, NGC 3311 shows weak radio emission with no jet-like feature around the core (Lindblad et al. 1985). These features rather suggest that the metal rich gas could be stripped off from NGC 3311. In this case, this galaxy is passing the core region and its location at the center may be a chance coincidence. The

very compact X-ray halo, like the one in NGC 3309, also suggests this possibility.

We have confirmed that the core region of A1060 has a smooth and circularly symmetric X-ray structure. The gas within $r < 15'$ is fairly isothermal with $kT \sim 3.2$ keV on $\sim 1'$ scales. Optical observations detected a huge void of about 50 Mpc extent in the front and back of the A1060 cluster. These features jointly suggest that the cluster has never experienced major mergers in the recent ~ 1 Gyr. Also, the central gas density of $3 \times 10^{-3} \text{ cm}^{-3}$ is lower than those in other cD clusters, resulting in a very long cooling time. Therefore, the formation process of A1060 may be going slowly and the cluster stays in a relatively young stage, which is also consistent with the low galaxy density in the surrounding region.

The surface brightness profile shows that the central cusp-like structure, reported by Tamura et al. (2000), is not due to the dark halo potential, rather it is a combination of the central galaxy NGC 3311 and the ICM. Even after subtraction of the central galaxy, the profile requires at least two components. The deviation from the single component model cannot be explained by an error in the approximation of the isothermal potential, and it seems that the gravitational potential itself has a double structure. Since A1060 is considered to be young and evolving, its potential may correspond to a structure taking place in an early phase of the cluster formation. If this is the case, the gravitational potential may gradually change its shape from a double to a single structure while the intracluster gas falls onto the center, as proposed by Ota (2001).

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